Title of Investigation:

Flux Transformers for Magnetic Calorimeter X-ray Detector Arrays

Principal Investigator:

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External Collaborators:

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Initiation Year:

FY 2003

Aggregate Amount of Funding Authorized in FY 2003 and Earlier Years:

$50,000

Funding Authorized for FY 2004:

$15,000

Actual or Expected Expenditure of FY 2004 Funding:

In-house: $15,000

Status of Investigation at End of FY 2004: Transition to other funding:

FY 2005 Internal Research and Development (IRAD)

Expected Completion Date:

September 2005

Purpose of Investigation:

We are investigating a new type of instrument—a high-performance X-ray calorimeter—that can measure X-rays emitted from the region near black holes and other celestial objects by converting the X-rays into heat pulses in an absorbing material and then measuring the small temperature rise in each pulse. Making instruments that can accurately measure the amount of heat deposited by a single X-ray photon with sufficient resolution is one of the technological advances required for future NASA missions, such as Constellation-X, Micro-Arcsecond X-ray Imaging Mission (MAXIM), Generation-X, and the Reconnection And Microscale (RAM) Solar-Terestrial Probe.

Goddard is actively developing two detector technologies, with the goal of demonstrating the required energy resolution. They include semi-conducting detectors, which will fly on the Astro-E2 mission, and superconducting detectors, which are being developed as a candidate for

Constellation-X. Both types of detectors measure temperature changes as a change in electrical resistance within the calorimeter.

We are now investigating a third type of detector—one that uses a magnetic material for which the degree of magnetism changes with temperature. This approach has shown to yield better energy resolution than the other two methods. However, tests of these devices so far have been performed with only a single pixel and future NASA missions will require thousands of pixels. In this project, we investigate a method to build a large array of magnetic calorimeters. Specifically, we examine whether thin-film flux transformers can provide an efficient means of transferring the magnetic signals from an array of X-ray absorbers and magnetic sensors fabricated on one silicon chip to an array of superconducting amplifiers fabricated on a separate chip.

Accomplishments to Date:

The approach we took was to use a superconducting planar transformer, with a slotted washer as a flux guide. The flux guide gives strong and equal magnetic coupling between any one of the many transformer coil windings and a magnetic sample near or overlapping the washer edge. When counter-flowing currents under each winding of the transformer coil encounter the slit in the washer, they turn mostly around the washer's inner edge. Thus, the slotted washer effectively translates the current from any transformer winding location to a current concentrated on the washer edge next to the sample, as illustrated in Figure 1.

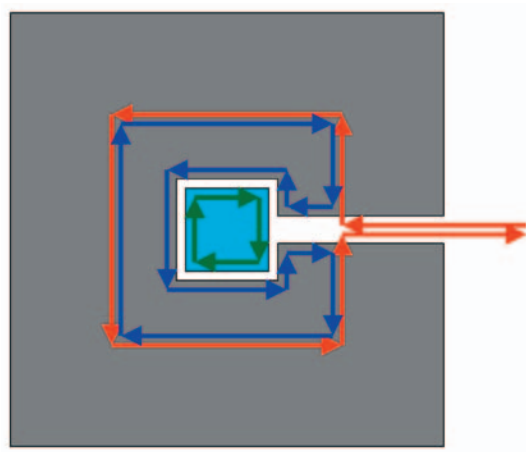

Figure 1. Sketch of current flowing in one turn of the transformer coil (red), counter-flowing current in slotted washer (blue), and effective current in sample (green)

We carried out detailed numerical modeling to optimize the design and predict achievable coupling strength. For a fixed sensor diameter and coil pitch, we calculated the optimum washer width for various assumed interconnect inductances. We solved for super-current distributions near the washer edge and calculated coupling strength at various positions within a three-dimensional sensor. We concluded that a compact transformer could be realized with coupling equivalent to only 2.7 times worse linear Superconducting Quantum Interference Device (SQUID) flux noise compared with placing the sample directly on the SQUID, (instead of two times worse for an ideal transformer).

We designed and procured photomasks, then fabricated arrays of flux transformers using optical lithography and reactive ion etching in the Goddard Detector Development Lab. Each chip (Figure 2a) has four 3 x 3 arrays of transformers. In the center of some transformers, we included a niobium ring (Figure 2b) that will screen down the self-inductance of the transformer coil to various degrees depending on the magnetic coupling strength at the ring location. In that way, we will be able to verify our modeling without the expense of depositing erbium-doped gold paramagnetic sensor layers during this Director's Discretionary Fund (DDF) project. A microstrip configuration gives very low inductance on-chip connections from coils to bonding pads (Fig. 2c).

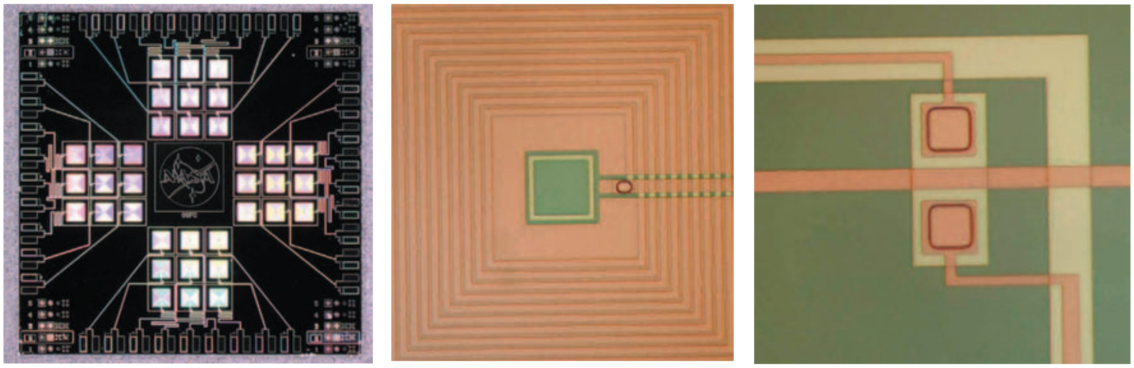

Figure 2. (a) Completed 12-mm square chip with four 3 x 3 transformer arrays. (b) View of center of transformer coil with niobium sample ring inside. Pitch of windings in niobium coil is 6 µm. (c) Microstrip connections and superconducting bias for crossovers.

In parallel with the fabrication work, we designed, built, and wired a testing platform in an Adiabatic Demagnetization Refrigerator (ADR), acquiring all the necessary SQUIDs and interconnection hardware. We were able to obtain SQUIDs with a suitably large input coil that is compatible with the SQUID electronics used with our TES detectors for the Constellation-X project. We adapted our TES testing box design to make a new mounting box for this work (Figure 3). With summer student help, we made and installed a field coil in the box lid capable of producing DC magnetic fields for biasing magnetic calorimeters.

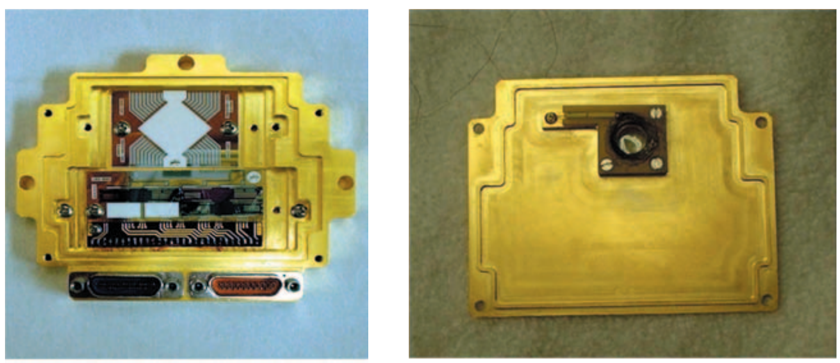

Figure 3. (a) Box developed for flux transformer measurements. (b) Underside of box lid showing field coil.

We characterized the SQUIDs in the detector box and measured the stray input inductance and shunt resistance of the input circuit by measuring the spectrum of Johnson noise at various sub-Kelvin temperatures. By measuring total inductance under different conditions, we will be able to characterize the flux transformer. We completed baseline measurements with a wirebond shorting our interconnecting leads together in place of the transformer chip. From this data, we measured the stray inductance of our interconnecting leads.

An extension request for more time to measure and analyze the performance of our flux transformers was approved for FY 2004. We found that a stray magnetic field in the ADR that we were using was interfering with our measurements. As an improved ADR (Figure 4a) was assembled and became available in the Goddard Space Flight Center X-ray Branch, we moved our test package to the new refrigerator (Figure 4b). New SQUID amplifiers, with larger input inductance more suited to our measurements, were recently delivered to us by collaborators at the National Institute of Standards and Technology (NIST). We incorporated the new SQUIDs, along with more reliable shunt resistors developed for Constellation-X, into the new package. We expect soon to complete inductance measurements of an array of our flux transformers (Figure 4c) under FY 2005 IRAD funding.

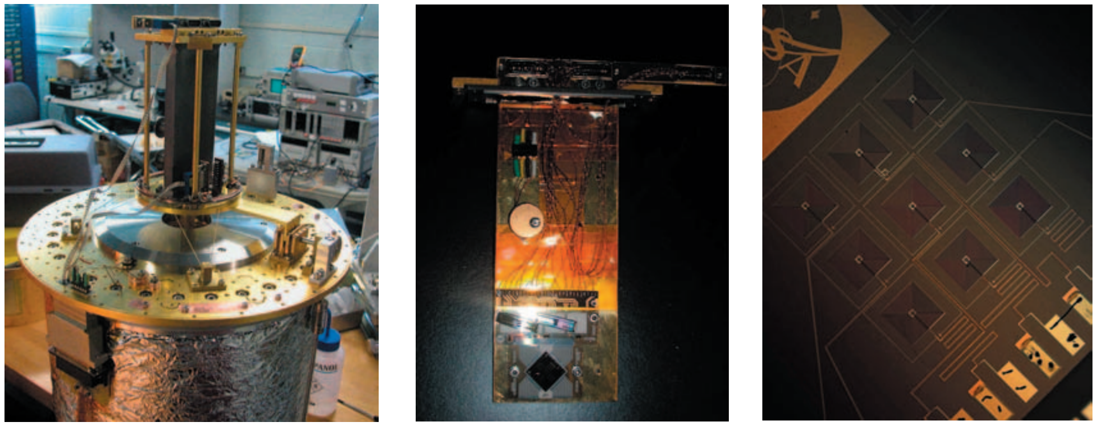

Figure 4. (a) ADR refrigerator. (b) Assembly with flux transformer and SQUID chips. (c) Transformer array.

The work we have accomplished so far was used to support proposals submitted in October 2003 to the Code R Mission and Science Measurement Technology NASA Research Announcement (NRA), and in June 2004 to the ROSS-APRA NRA. The Code R proposal was not awarded. The ROSS proposal is still pending.

Planned Future Work:

An Internal Research and Development (IRAD) proposal to purchase a gold-erbium deposition system for magnetic calorimeters was funded in FY 2004. Under a FY 2005 award, we will integrate our flux transformers with functional magnetic calorimeters and improve the performance of these transformers so that the signal is optimally coupled to the read-out SQUID amplifier. Furthermore, if selected, our ROSS proposal would allow Goddard to build upon the work of this investigation and an FY 2003 DDF on mushroom absorbers for magnetic calorimeters.

Summary:

This work experimentally demonstrates the feasibility of transferring magnetic signals with reasonable efficiency between an array of X-ray calorimeters and an array of readout amplifiers fabricated on separate silicon chips. This innovation will be an enabling technology for the development of large-format X-ray detectors based upon magnetic calorimeters and would help make this detector technology available to Goddard for use in the Constellation-X, MAXIM, Generation-X, and RAM missions. The criterion for success is demonstration of the feasibility of efficient transformer coupling to arrays of detectors. The risks have been unforeseen fabrication and testing difficulties and potential discrepancies between measured and predicted coupling. In fact, more sophisticated modeling than had been anticipated was found necessary to assure confidence in our design. We also experienced difficulty reproducing a dry etch process we had previously developed for niobium. As a result, design and fabrication steps took extra time and an extension into FY 2004 was required to complete measurements of magnetic coupling efficiency. We will continue this development effort as part of a FY 2005 IRAD award.